PATENT APPLICATION

TUNABLE LIGHT SOURCE EMPLOYING OPTICAL PARAMETRIC OSCILLATION NEAR DEGENERACY

INVENTORS

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FIELD OF THE INVENTION

The present invention relates generally to tunable light sources, and more particularly to using the process of optical parametric oscillation (OPO) near degeneracy to obtain a light source with a wide and stable tuning range.

BACKGROUND OF THE INVENTION

The continuing optics revolution is bringing about changes in many fields of technology. For example, fiber-optic networks employing dense wavelength division multiplexing (DWDM) are becoming increasingly pervasive as the backbone of modern communications systems. At the same time, machining devices employing lasers for precision processing, e.g., cutting, scribing and/or polishing of various materials including biological tissue are displacing traditional mechanical equipment. In still other fields, laser-based systems are being adapted for display purposes.

The above-mentioned technologies, as well as many others, require light sources with appropriate performance parameters. Specifically, there is a demand for tunable light sources, i.e., tunable lasers that can be tuned over a wide range of wavelengths. Such tunable light sources should additionally

exhibit excellent spectral characteristics, e.g., clean and narrowband output as well as absence of mode hops and/or power fluctuations during the tuning process. Furthermore, suitable light sources need to be simple in construction, versatile, and economical.

Such tunable laser sources are desired, for instance, in swept wavelength testing of passive and active telecommunication components. Testing a component can include, for example, measuring transmission, reflection or loss for any combination of the component's ports as a function of wavelength. Swept wavelength testing requires a very wide tuning range and/or a narrow test beam spectrum. In some cases a tuning range of 250 nm with a 0.1 to 10 pm test signal bandwidth is required. In addition to the swept wavelength approach, optical component testing can also be performed by a step-and-measure approach, by measurements at discrete wavelengths, or other variants of combining the tuning properties of the laser with measurements of relevant data. In this document, the term swept wavelength testing is intended to include these variants. Tunable laser sources are also employed in multi-channel coherent communication systems, spectroscopic measurements, and optical amplifier characterizations.

The prior art teaches the use of extended (or external) cavity diode lasers (ECDLs) to provide tunable laser sources for swept wavelength testing in telecommunications and other applications. A detailed description of external cavities is well documented in the art, for example, in "Spectrally Narrow Pulsed Dye Laser without Beam Expander" by Littman et al., Applied Optics, Vol. 17, No. 14, pp. 2224-2227, July 15 1978; "Novel geometry for single-mode scanning of tunable lasers" by Littman et al., Optics Letters, Vol. 6, No. 3, pp. 117-118; "External-Cavity diode laser using a grazing-incidence diffraction grating" by Harvey et al., Optics Letters, Vol.

16, No. 12, pp. 910-912; and "Widely Tunable External Cavity Diode Lasers" by Day et al., SPIE, Vol. 2378, pp. 35-41.

In a tunable ECDL the wavelength range is determined by the gain bandwidth of the lasing medium while wavelength selection and tuning functions are external to the gain element. These functions are typically accomplished by adjusting a total optical length L of the external cavity and its spectral response or passband. A diffraction grating and a movable mirror can be used for these purposes. The number of nodal points of the standing wave in the laser cavity is proportional to L/λ, where λ is the operating wavelength and L is the total optical length of the laser cavity (primarily provided by the length L_{ext} of the external cavity). Therefore, if the wavelength tuning takes place while L is maintained constant, the number of nodal points in the laser cavity changes discontinuously. That is, the wavelength cannot be continuously varied, but rather, it leaps in discrete steps - termed as mode-hops. As a result, it is often difficult to tune in a desired wavelength, and there may also be substantial fluctuations in the output power of the laser.

The prior art teaches to mitigate or avoid mode-hops by varying the length L of the laser cavity as wavelength tuning is taking place. Coordinating the wavelength tuning and the cavity-length change in ECDLs has been a rather arduous and expensive undertaking. Documentation of further efforts to prevent mode-hops and provide more continuous tuning are found in U.S. Patent Nos. 5,172,390, 5,319,668, 5,347,527, 5,491,714, 5,493,575, 5,594,744, 5,862,162, 5,867,512, 6,026,100, 6,038,239, and 6,115,401.

Diode lasers typically have gain bandwidths (and therefore tuning ranges) of about 1-5% of the optical wavelength, or

about 30 nm if centered near 1550 nm. Some diode lasers which are optimized for broad gain bandwidth (at the expense of other properties) can have somewhat larger gain bandwidths. Therefore, external cavity diode lasers with tuning ranges of about 50-100 nm are now commercially available. However, tuning ranges approaching 250 nm are extremely difficult or impossible to achieve with a diode laser despite all the efforts documented in the prior art.

In U.S. Pat. No. 6,134,250 the inventors describe a single-mode wavelength selectable ring laser, which operates at a single wavelength selectable from any channel passband of a multiple-channel wavelength multiplex/demultiplex element (e.g., an arrayed waveguide grating router (AWGR)). A Fabry-Perot semiconductor optical amplifier (FP-SOA) is connected to AWGR to form a ring laser structure, where FP-SOA is used as an intra-cavity narrow-band mode-selecting filter to stabilize the laser oscillation to a single axial mode. As such, this ring laser system can only provide discrete tuning from one wavelength passband of the wavelength filter to another. That is, continuous tuning cannot be achieved in this system. Hence, this prior art laser system is suited for providing a wavelength-selectable laser, as opposed to a wavelength tunable laser.

Prior art also suggests turning to other types of lasers and elements to achieve a wide and stable wavelength tuning range. Unfortunately, none of the prior art systems has the desired parameters. Specifically, the gain bandwidths for the most promising of these lasers are limited, e.g., Erbium based lasers have gain bandwidths of about 30 nm to about 100 nm, SOA has a gain bandwidth of about 30 nm and ECDLs have gain bandwidths of about 100 nm. These gain bandwidths make it impossible to provide for tuning ranges up to 250 nm or more. Furthermore, these laser sources are not sufficiently simple

in construction, versatile, and economical. Combining a number of them, e.g., stitching together several ECDLs to cover a tuning range of 250 nm, is not a practical solution. This is because it is difficult to control the tuning behavior or achieve accurate wavelength control of combined sources. Furthermore, combined sources can not be tuned as rapidly as some applications require. Also, an implementation including a combination of multiple sources is generally more expensive relative to a single source which covers the required wavelength range.

In order to generate light in certain wavelength ranges where laser sources are not available (e.g., due to lack of lasing media generating light in those wavelength ranges at sufficient power levels) the prior art prescribes the use of nonlinear optics methods. Nonlinear optics encompass various processes by which a nonlinear optical material exhibiting a certain nonlinear susceptibility converts input light at an input wavelength to output light at an output wavelength in the difficult to access wavelength range. Some well-known nonlinear processes involving light at two or more wavelengths (e.g., three-wave mixing and four-wave mixing) include second harmonic and higher harmonic generation, difference frequency generation, sum frequency generation and optical parametric generation. The fundamentals of nonlinear optical processes are discussed extensively in literature and the reader is referred to Amnon Yariv, *Quantum Electronics*, 2nd edition, Wiley Press, 1967 for general information.

Specific methods and devices using nonlinear wavelength conversion to produce light sources are also taught by the prior art. For example, M.H. Chou et al., "1.5-μm-band wavelength conversion based on difference-frequency generation in $LiNbO_3$ waveguides with integrated coupling structures", Optics Letters, Vol. 23, No. 13, 1 July, 1998 teach optical

frequency mixing in the 1.5 μm wavelength band for telecommunication purposes. Additional information related to nonlinear wavelength conversion for communications applications can be found in I. Brenner et al., "Cascaded $\chi^{(2)}$ wavelength converter in $LiNbO_3$ waveguides with counter-propagating beams", Electronics Letters, Vol. 35, No. 14, 8 July 1999; and M.H. Chou et al., "Stability and bandwidth enhancement of difference frequency generation (DFG)-based wavelength conversion by pump detuning", Electronics Letters, Vol. 36., No. 12, 10 June, 1999.

The output light from nonlinear wavelength converters can be tuned over a certain wavelength range. In general, control of the wavelengths of the mixing or interacting light beams can be used to adjust the output wavelength. When the nonlinear conversion process takes place in materials specially engineered to achieve high nonlinear conversion efficiencies, e.g., materials using quasi-phase-matching (QPM) gratings in in-diffused waveguides, control over certain grating parameters (i.e., the phasematching condition) can be employed to achieve output wavelength tuning. For general information on this subject the reader is referred to Michael L. Bortz's Doctoral Dissertation entitled "Quasi-Phasematched Optical Frequency Conversion in Lithium Niobate Waveguides", Stanford University, 1995 as well as M.L. Bortz et al., "Increased Acceptance Bandwidth for Quasiphasematched Second Harmonic Generation in $LiNbO_3$ Waveguides", Electronics Letters, Vol. 30, 1/6/1994, pp. 34-5. Additional information on devices using QPM gratings for nonlinear conversion in found in U.S. Pat. No. 5,875,053. The processes used to make QPM gratins are described in U.S. Pat. No's. 5,800,767 and 6,013,221, and waveguides with QPM gratings employed for nonlinear optical processes are described in U.S. Pat. No. 5,838,720.

Some specific high power pumped mid-IR wavelength systems using non-linear frequency mixing to obtain tunable light sources are taught by Sanders et al. in U.S. Pat. No. 5,912,910. In particular, the inventors teach the use of a narrowly tunable difference frequency generation and widely tunable optical parametric oscillation for generating output light in the desired mid-IR wavelength range. The phasematching bandwidth (e.g., of the QPM grating) is used for output bandwidth control for the OPO case. Unfortunately, due to their construction and the use of phasematching bandwidth for output linewidth control the OPO light sources of Sanders et al. still exhibit tuning instability due to mode-hopping as well as large output wavelength linewidths.

The use of optical parametric oscillation for producing a continuously tunable, short pulse and high repetition rate light source is also taught by Kent Burr et al., "High-repetition-rate femtosecond optical parametric oscillator based on periodically poled lithium niobate", Applied Physics Letters, Vol. 70, 1997, pg. 3343. The tuning bandwidth for the idler beam in this OPO extends from 1.68 μm to 2.72 μm and for the signal beam from 1.12 μm to 1.50 μm. Tuning is achieved by either temperature control of the nonlinear optical element within which OPO takes place, or tuning the wavelength of the pump beam driving the optical parametric oscillation or by adjusting the length of the cavity in which the nonlinear optical element was placed. Although low threshold for generation of output light in the form of the idler beam was achieved, these methods of controlling the OPO process do not yield a sufficiently stable and continuously tunable narrow linewidth output light desired. Furthermore, the process tends to set up double resonance (of both the idler beam and the signal beam) within the cavity when the signal and idler wavelengths are near 1560 nm. Above that, the system taught is large and bulky.

Finally, the use of OPO for a tunable source is again addressed by Mark A. Arbore et al. in "Singly resonant optical parametric oscillation in periodically poled lithium niobate waveguides", Optics Letters, Vol. 22, No. 3, 1 Feb. 1997. In this case the resonant cavity is singly resonant (only at the signal wavelength) and the output wavelength (signal or idler wavelength) is efficiently generated and tuned over several hundreds of nanometers in bandwidth. The OPO is performed close to degeneracy at which the wavelengths of the signal and idler beams are equal, and the pump has half the wavelength of the signal or idler beam. Although this teaching goes far in providing a widely tunable and fairly stable light source using OPO, its output still suffers from instability and insufficiently narrow output linewidth. In fact, the output linewidth was about 4 nm, about 1,000 times too large for any practical application to swept wavelength testing, and the axial mode spacing was 2.6 GHz, causing mode-hops.

In view of the foregoing, there is still an unfilled need for a stable, simple and tunable light source having a wide tuning range, preferably over 250 nm, and a narrow output linewidth. Specifically, there is a need for an efficient, economical and widely tunable light source which can be used for practical applications in various fields of optics.

OBJECTS AND ADVANTAGES

It is therefore a primary object of the present invention to provide a tunable light source which has a wide tuning range, preferably in excess of 250 nm, over which the output wavelength is stable and can be continuously tuned.

It is a further object of the invention to take advantage of the nonlinear process of optical parametric oscillation to obtain the tunable light source.

Furthermore, it is also an object of the invention to ensure that the tunable source is easy to make and control, as well as economical and well-suited for practical applications.

These and other objects and advantages of the invention will become apparent upon further reading of the specification.

SUMMARY

The objects and advantages are achieved by a tunable light source equipped with an optical parametric amplifier (OPA) placed in a cavity for performing an optical parametric oscillation (OPO) involving a signal beam and an idler beam. The optical parametric oscillation is driven by a pump beam at a pump frequency provided to the OPA from a pump arrangement. The pump frequency is within a certain range such that the OPO is driven near degeneracy. In other words, the pump frequency is chosen such that the frequencies of the signal and idler beams are close (degeneracy being defined as the point at which these two frequencies are equal). The pump frequency tuning range expressed in terms of a wavelength tuning range is about 1.5 nm around degeneracy. The tunable source has an adjustment mechanism for adjusting the pump frequency within this wavelength tuning range and to thereby select a gain spectrum of the OPO. This gain spectrum is represented by the wavelength ranges over which the idler and signal beams experience gain. Additionally, the tunable light source has a

spectral control mechanism for setting a resonant frequency of the cavity within the gain spectrum.

Conveniently, the spectral control mechanism is a narrowband tuner with its passband set or centered at the resonant frequency. The narrowband tuner can be a diffraction grating filter, a tunable fiber Bragg grating, dielectric coated mirrors, dielectric coated filters or an etalon filter. In addition to serving the primary function of selecting a particular resonant frequency within the gain spectrum, the spectral control element is also conveniently set to reject one of the idler and signal beams. In other words, only one of the idler and signal beams within the passband set by the narrowband tuner, i.e., at the resonant frequency is supported inside the cavity.

In the same or in another embodiment the cavity is a multiple axial mode cavity such that it supports a number of axial modes at the resonant frequency. The cavity can be a standing-wave type cavity or a ring cavity. Preferably, the cavity includes an optical fiber and is longer than 1 meter. It is also preferred, that the cavity be used in conjunction with the narrowband tuner for controlling the resonant frequency within the cavity.

The pump arrangement for supplying the pump beam for driving the OPO can take on any number of forms. However, it is most convenient to obtain the pump beam by relying on the nonlinear operation of second harmonic generation (SHG) to frequency double a primary beam. Thus, the pump arrangement has a light

source for producing the primary beam and a second harmonic generator for receiving and frequency doubling the primary beam to produce the pump beam. The pump arrangement can also include a suitable optical amplifier, e.g., a fiber amplifier, for amplifying the primary beam.

When a second harmonic generator is used to obtain the pump beam it is convenient that both the second harmonic generator and the optical parametric amplifier be contained in the same nonlinear optical converter. This goal can be accomplished since the same nonlinear materials can be used for both second harmonic generation and optical parametric oscillation. After second harmonic generation produces the pump beam the primary beam is no longer needed. Therefore, a wavelength filter can be positioned between the second harmonic generator and the optical parametric amplifier for filtering the primary beam. Suitable wavelength filters for this purpose include a spatial mode filter, a grating, a fiber Bragg filter, a low pass filter, a directional coupler, a dichroic dielectric mirror, a grating-assisted coupler and an absorptive filter. Alternately, the residual primary beam could be further used, for example in a resonant multiple-pass configuration. In this case, the intervening filter should be chosen to provide separation of the primary beam with low loss.

In one embodiment the second harmonic generator has a first quasi-phase-matching (QPM) grating in the nonlinear optical converter and the optical parametric amplifier has a second quasi-phase-matching grating in the same nonlinear optical converter. Appropriate grating parameters are selected for

phasematching the second harmonic generation and optical parametric amplification in the first and second QPM gratings, respectively. The first QPM grating for performing the second harmonic generation can be a grating with a uniform grating period or an aperiodic grating period. Preferably, the length and/or pattern of this first QPM grating is sufficient to enable efficient second harmonic generation over a bandwidth of at least 2 nm and preferably more than 3 nm for the primary beam. In addition, the two QPM gratings can be separated by a certain distance and an optical coupler can be disposed between the first and second QPM gratings for coupling in the signal beam and/or idler beam for the optical parametric amplification taking place in the second QPM grating. In this or another embodiment, it is advantageous that the QPM gratings be distributed in a waveguide fabricated in the nonlinear optical converter.

The tunable light source also has an output coupler for out-coupling at least one of the signal and idler beams. Depending on the operation, either the signal or the idler beam (or even both) can be used as the useful output of the tunable light source.

In one embodiment, the tunable light source is additionally equipped with a wavelength sweep control. The wavelength sweep control coordinates the adjustment of the pump frequency, which sets the gain spectrum, with the selection of the resonant frequency by the spectral control mechanism. Specifically, the sweep control coordinates a scan or sweep of the resonant frequency across a wavelength window. The

wavelength window can have a bandwidth of 250 nm or more. For example, in swept wavelength testing applications the wavelength window can be 250 nm centered at approximately 1550 nm. Also, for the purposes of swept wavelength tests the passband for the resonant frequency can be set between 0.1 to 1000 pm, resulting in 0.1 to 100 pm output spectrum width. Furthermore, in some embodiments the tunable light source has a synchronizing unit connected to the pump arrangement for synchronizing the pump beam with a round-trip time of the cavity.

In a particular embodiment, the tunable light source is used in a swept wavelength system. The swept wavelength system preferably includes the wavelength sweep control for performing optical tests.

In another embodiment of the swept wavelength system the tunable light source has the nonlinear optical converter placed in the cavity for performing a nonlinear frequency conversion other than optical parametric amplification. For example, the nonlinear frequency conversion operation can be second harmonic generation, difference frequency generation or sum frequency generation. In all of these embodiments the nonlinear optical converter has a QPM grating for phase matching the nonlinear frequency conversion.

The present invention also provides for a method for tuning the light source using the OPA for obtaining a widely tunable output. Specifically, the method calls for producing the pump beam at the pump frequency and delivering the pump beam to the

OPA for driving the optical parametric oscillation involving the idler and signal beams. Furthermore, the method calls for adjusting the pump frequency to select a gain spectrum for the OPO and setting the resonant frequency of the cavity within this gain spectrum. The OPO is then driven near degeneracy by the pump beam. The wavelength tuning range for the pump beam is approximately 1.5 nm around degeneracy.

In one embodiment, the spectrum control is achieved by establishing a passband for at least one of the idler and signal beams. In some embodiments the passband is set between 0.1 pm and 1000 pm. In the embodiments where the passband is obtained with the aid of a narrowband tuner, the tuner can be additionally used to remove one of the idler and signal beams. This removal can be based on which beam is the useful output of the tunable light source. The narrowband tuner can also be used to remove one or both of the primary beam or pump beam.

The pump beam can be delivered to the OPA in several formats. Specifically, the pump beam can be a continuous-wave beam or a pulsed beam. For example, in the event of a pulsed beam, the beam can have a duty cycle (on time) ranging from 1% to 50%. Duty cycle is defined as the pulse duration divided by the interpulse time. Of course, other duty cycle ranges can also be used, although they may result in widening of the resonant frequency bandwidth, slow tuning, low pulse frequency or all of these. In a preferred embodiment of the method, the pump beam is pulsed and synchronized with a round-trip time of the cavity. For example, the pulse repetition time of the pump beam can be synchronized to equal the cavity round-trip time,

an integral number of round trip times or an integral fraction of a round-trip time. The pulse repetition time can also be adjusted to be many times longer than the round-trip time, e.g., to obtain quasi-continuous-wave operation of the light source. The pulse repetition time and pulse length can also be adjusted to provide a quasi-continuous-wave output with regard to the system using the source. This can be done by making the pulse repetition rate high relative to the frequency sensitivity of the system, or by making the pulse long relative to the response time of the system. The former is commonly referred to as "quasi-cw", while the latter is commonly referred to as "quasi-static", and the former is preferred.

In operating the tunable light source the point of degeneracy is avoided. Specifically, the tunable light source is preferably operated near degeneracy but within a certain offset from degeneracy itself. Specifically, operation in a region where the separation between signal beam and idler beam is comparable to or less than the passband of the spectral control mechanism is avoided. Thus, for example, the offset can range from 1 to 1000 pm and preferably from 50 pm to 500 pm.

As will be apparent to a person skilled in the art, the invention admits of a large number of embodiments and versions. The below detailed description and drawings serve to further elucidate the principles of the invention and some of its embodiments.

BRIEF DESCRIPTION OF THE FIGURES

Fig. 1	is a simplified diagram illustrating the essential parts of a tunable light source according to the invention.
Figs. 2A-C	illustrate the fundamentals of the operation of the tunable light source of Fig. 1
Fig. 3	is an isometric view illustrating a preferred embodiment of a tunable light source according to the invention.
Fig. 4	is a graph illustrating the gain spectra for the light source of Fig. 3.
Fig. 5	is a graph illustrating the tuning behavior of the light source of Fig. 3.
Fig. 6A	is a plan view illustrating several details of the nonlinear optical converter used by the light source of Fig. 3.
Fig. 6B	is a plan view illustrating another embodiment of a nonlinear optical converter in accordance with the invention.
Fig. 7	is a diagram of another embodiment of a tunable light source according to the invention.
Fig. 8	is a diagram of a tunable light source for swept wavelength testing in accordance with the invention.

DETAILED DESCRIPTION

The fundamentals of the invention will be best understood by initially referring to a tunable light source **10** in accordance with the invention, as shown in Fig. 1. Light source **10** has a pump arrangement **12** for providing a pump beam **14** at a pump frequency ω_p. Pump beam **14** is pulsed and consists of individual pulses **16** (only one pulse **16** is shown for reasons of clarity). Pump arrangement **12** can employ a pulsed laser,

e.g., a Q-switched laser able to provide sufficiently high power in primary beam **14**, e.g., several hundred miliWatts of peak power in each of pulses **16**. A person skilled in the art will recognize that it is also possible for pump arrangement **12** to employ a continuous-wave laser, a near-continuous-wave laser or an externally modulated cw laser, provided that it yields sufficient power levels for the frequency conversion operations described below.

Light source **10** has an adjustment mechanism **18** connected to pump arrangement **12** for adjusting pump frequency ω_p of pump beam **14**. Adjustment mechanism **18** can be any suitable device capable of controlling the temperature or any other parameter, e.g., cavity length of the laser used by pump arrangement **12**, to tune pump frequency ω_p of pump beam **14**. Specifically, more conveniently expressed in terms of a wavelength tuning range, pump beam **14** should be tunable by about 1.5 nm or more. In addition, adjustment mechanism **18** should be able to perform the tuning across this wavelength tuning range as rapidly as feasible, e.g., on the order of seconds or tens of seconds. A person skilled in the art will appreciate that any suitable technique for obtaining this tuning range in pulsed, near-continuous-wave and continuous-wave lasers can be applied to obtain the desired tuning range.

Light source **10** is equipped with an optical parametric amplifier (OPA) **20** positioned in a cavity **22**. OPA **20** is made of a nonlinear optical material selected for its nonlinear susceptibility, i.e., its second order nonlinear

susceptibility $\chi^{(2)}$, as well as any other requisite properties required for performing optical parametric amplification. OPA **20** also includes any suitable phasematching arrangement for phasematching the operation of optical parametric amplification within OPA **20**.

Cavity **22** is delimited by two mirrors **24** and **26**. Pump beam **14** is in-coupled into cavity **22** through mirror **24**, which serves as the input coupler. Mirror **26** serves as the output coupler from cavity **22**.

A spectral control mechanism **28** is also located inside cavity **22**. Spectral control mechanism **28** is a narrowband tuner or any other suitable optical filtering device. Spectral control mechanism **28** is provided for setting a resonant frequency $\omega_{res.}$ of cavity **22** as discussed below.

The operation of tunable light source **10** will be best understood by initially reviewing Figs. 2A and 2B. OPO is a process during which pump beam **14** at pump frequency ω_p transfers power to a signal beam **30** at frequency ω_S and to an idler beam **32** at frequency ω_I according to the equation:

$$\omega_p = \omega_S + \omega_I .$$

The process is performed such that energy and momentum are conserved between the photons constituting the three interacting beams. In the case where $\omega_S=\omega_I=\omega_{p/2}$ the OPO is

called degenerate and is essentially the opposite of second harmonic generation (SHG), such that:

$$\omega_p = 2\omega_{p/2}.$$

In other words, degeneracy is encountered when frequency ω_S of signal beam **30** and frequency ω_I of idler beam **32** are equal to each other, and therefore equal to half of pump frequency ω_p of pump beam **14** which is driving the OPO. This condition is illustrated in Fig. 2A, where the corresponding pump frequency ω_{po} of pump beam **14** indicated by a solid arrow produces signal beam **30** and idler beam **32** indicated by two solid arrows both at frequency $\omega_{po/2}$ ($\omega_S=\omega_I=\omega_{po/2}$).

Reviewing this situation in still more detail we find that pump beam **14** at the specific pump frequency ω_{po} OPO exhibits gain within a gain spectrum **34**. In other words, when OPA **20** is driven by pump beam **14** at the specific pump frequency ω_{po}, OPA **20** offers gain for signal and idler beams **30, 32** within gain spectrum **34**. In Fig. 2A signal and idler beams **30, 32** are indicated by arrows at the maximum of gain spectrum **34** centered at one half of the pump frequency or at $\omega_{po/2}$.

When pump beam **14** is tuned by adjustment mechanism **18** gain spectrum **34** for OPO within OPA **20** shifts. For example, for two specific pump beams designated by **14′** and **14″** and associated with pump frequency values $\omega_{p'}$ and $\omega_{p''}$ gain spectrum

34 of OPA **20** is shifted to **34′** and **34″**, respectively. Gain spectra **34′**, **34″** each have two separate gain regions in which signal beams **30′**, **30″** and idler beams **32′**, **32″** experience gain. The corresponding signal and idler frequencies $\omega_{S'}$, $\omega_{S''}$ and $\omega_{I'}$, $\omega_{I''}$ are indicated as center frequencies of gain spectra **34′**, **34″**.

According to the invention, mechanism **18** tunes pump frequency ω_p over a range conveniently expressed in terms of wavelength as a wavelength tuning range **36**. Tuning range **36** corresponds to about 1.5 nm around degeneracy. As pump frequency ω_p is tuned over tuning range **36** the gain spectrum for signal and idler beams **30**, **32** shifts, as discussed above. In fact, as pump frequency ω_p sweeps over entire tuning range **36**, gain spectrum covers a frequency range conveniently expressed in the form of a wavelength window **40**. For tuning range **36** of 1.5 nm, wavelength window **40** is about 250 nm wide. Of course, extending tuning range **36** past 1.5 nm will enlarge wavelength window **40**. It should be noted, however, that using pump frequency ω_p considerably outside tuning range **36** will reduce or even eliminate the advantages of the invention.

Fig. 2B illustrates the operation of spectral control mechanism **28** in the particular case of pump beam **14″** tuned to pump frequency $\omega_{p''}$. At pump frequency $\omega_{p''}$ one obtains gain spectrum **34″** with two gain portions centered at the indicated signal and idler frequencies $\omega_{S''}$ and $\omega_{I''}$ corresponding to signal and idler beams **30″**, **32″**. In accordance with the

invention, a passband **44** of spectral control mechanism **28** is used to choose a resonant frequency $\omega_{res.}$ of cavity **22** within gain spectrum **34″**. In other words, passband **44** selects a portion of gain spectrum **34″** within which cavity **22** will support a resonant beam **46** (see Fig. 1) at resonant frequency $\omega_{res.}$. In the present embodiment, passband **44** covers a portion of gain spectrum **34″** centered at signal frequency $\omega_{S''}$. Thus, resonant frequency $\omega_{res.}$ supported by cavity **22** corresponds to the central narrowband portion of gain spectrum **34″**. In fact, the center frequencies for signal beam **30″** and resonant beam **46** are equal.

Preferably, passband **44** is very narrow, e.g., in the range of 0.1 pm to 1000 pm. Thus, only about 0.1 pm to 1000 pm of signal beam **30″** represents resonant beam **46**. It should be noted that with passband **44** set for only one resonant frequency $\omega_{res.}$ cavity **22** is singly resonant; i.e., only single resonant beam **46** is supported. A person skilled in the art will recognize that proper positioning of passband **44** within gain spectrum **34″** allows the user to select narrowband portions of either signal beam **30″** or idler beam **32″** as resonant beam **46**.

In some embodiments spectral control mechanism **28** has a second passband **44′** centered on a portion of gain spectrum **34″** at idler frequency $\omega_{I''}$, as indicated in Fig. 2B. In this case two resonant beams **46, 46′** at resonant frequencies $\omega_{res.}$ and $\omega'_{res.}$ are supported by cavity **22**, which is now doubly resonant. In

general, and especially when operating light source **10** close to degeneracy, as defined below, singly resonant cavity **22** is preferred and in this case resonant beam **46** is the only useful beam out-coupled from cavity **22** through output coupler **26.**

The mathematical definition of degeneracy has been previously provided and corresponds to the operating point where pump, signal and idler beams are related by $\omega_S=\omega_I=\omega_{p/2}=\frac{1}{2}\omega_p$. Herein, the working definition of degeneracy is the operating condition when pump frequency ω_p of pump beam **14** and passband **44** are related such that the frequency $\frac{1}{2}\omega_p$ or $\omega_{p/2}$ is included within passband **44.** This means that the wavelength separation between signal and idler beams **30, 32** should be maintained at least equal and preferably larger than passband **44** to which resonant frequency $\omega_{res.}$ is confined.

Under the above definition degeneracy already occurs when pump frequency ω_p is within an offset **48** from mathematical degeneracy at pump frequency ω_{po} as indicated in Fig. 2A. In most cases offset **48** will be on the order of 100 pm. A person skilled in the art will recognize, however, that offset **48** will vary based on many factors such as the width of passband **44** set by spectral filter **28,** the spectral filter shape and the loss of cavity **22.** Hence, the quality of resonant beam **46** output from cavity **22** can be used as an empirical measure to determine offset **48** from ω_{po} for pump frequency ω_p.

In accordance with the invention, light source **10** is operated such that the OPO is driven near degeneracy. In terms of pump wavelength, the region of near degeneracy extends from the value of pump frequency at offset **48** to the value of pump frequency at the end of tuning range **36**. The region outside tuning range **36** is considered far from degeneracy.

Clearly, resonant beam **46** at resonant frequency $\omega_{res.}$ can be set for any frequency within wavelength window **40** by first tuning pump frequency ω_p to produce gain at the desired signal frequency ω_S or idler frequency ω_I and then setting passband **44** centered at the desired resonant frequency $\omega_{res.}$. Since the gain spectrum is set with the aid of adjustment mechanism **18** and passband **44** is selected with the aid of spectral control mechanism **28** their operation should be coordinated. In this manner resonant beam **46** can be made to sweep the entire wavelength window **40** of about 250 nm. The speed of this sweep will depend on the speed with which adjustment mechanism **18** can adjust pump wavelength ω_p and the speed with which spectral control mechanism **28** is able to set passband **44** at the desired resonant frequency $\omega_{res.}$.

It is important to note that wavelength window **40** is not discontinuous at degeneracy and resonant beam **46** near and strictly at degenerate frequency $\omega_{po/2}$ can be generated by light source **10**. For this purpose, $\omega_{res.}$ is tuned through degeneracy and even set at $\omega_{po/2}$ while not using pump frequency

ω_{po} (at which strict degeneracy is encountered) to drive the OPO. Pump frequency ω_p of pump beam **14** is set by adjustment mechanism **18** at offset **48** to produce gain spectrum **34A**, as illustrated in Fig. 2C. Now, spectral control mechanism **28** sets passband **44** centered on $\omega_{po/2}$ such that $\omega_{po/2}=\omega_{res.}$. Thus, resonant beam **46** output from cavity **22** is at frequency $\omega_{po/2}$. However, OPO is not mathematically degenerate because $\omega_{res.}\neq\omega_{p/2}$. If $\omega_p<\omega_{po}$, then $\omega_{res.}$ is ω_s and $\omega_i<\omega_{res.}$ If $\omega_p>\omega_{po}$, then $\omega_{res.}$ is ω_i and $\omega_s>\omega_{res.}$. In either case, OPA **20** is not mathematically degenerate and the source is not operating as a doubly-resonant OPO or DRO.

Tunable light source **10** of the invention thus provides a continuously and widely tunable output in the form of resonant beam **46**. The wavelength window **40** over which resonant beam **46** is tunable is sufficiently large for applications in many fields of optics, including communications and swept wavelength testing. The components and principles of operation of light source **10** can be modified in many ways to suit the particular performance characteristics desired.

Fig. 3 illustrates a preferred embodiment of a tunable light source **50** with pump arrangement **52** employing a directly modulated diode laser **53** centered at wavelength of about 1530 nm. Diode laser **53** produces a primary beam **54** at a primary frequency $\omega_{pr.}$. An adjustment mechanism **58** tunes primary frequency $\omega_{pr.}$ and modulates diode laser **53** to emit in pulses **56** (only one pulse shown for reasons of clarity).

A nonlinear optical converter **60** is positioned in the path of primary beam **54**. Nonlinear optical converter **60** is made of a nonlinear optical material such as $LiNbO_3$ and has a first waveguide **62** with an in-coupling section **64**, in this case in the form of a taper, for in-coupling primary beam **54**. Conveniently, waveguide **62** is an annealed proton-exchanged waveguide produced in $LiNbO_3$. Nonlinear optical converter **60** contains a second harmonic generator (SHG) **66** followed by an optical parametric amplifier (OPA) **68**, both positioned inside waveguide **62**.

SHG **66** is a part of pump arrangement **52** and is intended for frequency doubling primary beam **54** obtained from diode laser **53** to generate a pump beam **78**. Specifically, SHG **66** has a quasi-phase-matching (QPM) grating **70** for phasematching the nonlinear operation of generating second harmonic (SH) beam **78** of primary beam **54**. Thus, SHG **66** converts pulses **56** of primary beam **54** at $\omega_{pr.}$ into pulses **79** of second harmonic beam **78** at pump frequency $\omega_p=2\omega_{pr.}$.

OPA **68** has a QPM grating **72** for phasematching the nonlinear operation of optical parametric amplification. It will be appreciated by a person skilled in the art that various types of nonlinear optical materials other than $LiNbO_3$ exhibiting suitable nonlinear susceptibility, i.e., second order nonlinear susceptibility $\chi^{(2)}$, as well as other requisite properties, e.g., the ability to support QPM gratings (or other phasematching techniques) and waveguides, can be used to

make nonlinear optical converter **60**. It will also be appreciated by a person skilled in the art that phasematching techniques not involving QPM gratings **70**, **72**, e.g., birefringence phase matching or waveguide modal phasematching can be employed for phasematching in SHG **66** and OPA **68**.

A wavelength filter **74** is located between SHG **66** and OPA **68** for removing or filtering out primary beam **54** from first waveguide **62** before OPA **68**. Filter **74** is used to prevent primary beam **54** from entering OPA **68** in the event primary beam **54** would interfere with optical parametric amplification driven by pump beam **78**. A person skilled in the art will recognize that filter **74** will become less useful (and can be completely left out) the further away from degeneracy the OPO is performed. Suitable wavelength filters for this purpose include spatial mode filters, gratings, fiber-Bragg filters, low pass filters, directional couplers, dichroic dielectric mirrors, grating-assisted couplers and absorptive filters. In the present embodiment wavelength filter **74** is a directional coupler.

Nonlinear converter **60** also has a second waveguide **76** with an in-coupling section **77** for in-coupling a resonant beam **80** at resonant frequency $\omega_{res.}$ arriving in pulses **82**. In-coupling section **77** is in the form of a taper in second waveguide **76**. Second waveguide **76** has a section **84** which extends along first waveguide **62**, creating a coupling junction or directional coupler **86** between waveguides **62** and **76**. Directional coupler **86** allows pulses **82** of resonant beam **80** to couple into

waveguide **62** via the evanescent field coupling effect. Furthermore, directional coupler **86** is designed so that it does not perturb the second harmonic or pump beam **78**. The mechanism of evanescent field coupling is well-known in the art. It should also be noted that methods and structures relying on physical processes other than evanescent field coupling, e.g., grating-assisted coupling, can be used for coupling resonant beam **80** into waveguide **62**.

Nonlinear optical converter **60** has an output coupler **88** located at the end of first waveguide **62**. Output coupler **88** is a narrowing taper in waveguide **62**. A signal beam **90**, an idler beam **92** and pump beam **78** emanating from OPA **68** are all out-coupled through output coupler **88**. Narrowing taper **88** is conveniently used to mode-match and couple the three output beams **90**, **92** and **78** into fiber for further transmission.

Tunable light source **60** has a spectral control mechanism **94** for controlling its spectrum. In the present embodiment, spectral control mechanism **94** is a narrowband tuner with a narrow passband, e.g., on the order of 100 pm, positioned after nonlinear converter **60**. Narrowband tuner **94** is connected to adjustment mechanism **58**. Narrowband tuner **94** can be a diffraction grating filter such as a TB9 series tunable optical grating filter available from JDS Uniphase, a tunable fiber Bragg grating, dielectric coated mirrors, dielectric coated filters or an etalon filter.

Nonlinear converter **60** and narrowband tuner **94** are located in a cavity **96**. Conveniently, cavity **96** is a ring cavity

employing a fiber loop **98**. Alternatively, cavity **96** can be a standing-wave cavity, as is known to those skilled in the art. In any case, cavity **96** is preferably long enough to support a number of axial modes, thereby further aiding in the continuous tuning of light source **50**. For example, cavity **96** has a length of at least 1 meter. Additionally, cavity **96** has an output coupler **100**, here in the form of a y-junction fiber coupler. A person skilled in the art will recognize that fused fiber couplers as well as other output coupling elements can be employed in alternative embodiments.

The operation of tunable light source **60** proceeds in accordance with the general principles explained above. With the aid of adjustment mechanism **58** a desired primary frequency $\omega_{pr.}$ is set for primary beam **54** emitted by diode laser **53**. Primary beam **54** is in-coupled into waveguide **62** via taper **64**. With the aid of QPM grating **70** primary beam **54** is efficiently frequency doubled in SHG **66** to yield pump beam **78** at pump frequency ω_p. (Primary beam **54** does not enter OPA **68** since it is filtered out by wavelength filter **74** before OPA **68**.) Pump frequency ω_p, in turn, determines the gain spectrum for optical parametric oscillation in OPA **68**. Fig. 4 illustrates the gain spectra in terms of wavelength for signal and idler beams **90**, **92** in OPA **68**. The gain spectra are indicated for several primary wavelengths $\lambda_{pr.}$ of primary beam **54** (rather than pump wavelengths λ_p of pump beam **78**). A person skilled in the art will appreciate that the actual gain spectra will differ for alternate nonlinear optical materials.

OPA **68** driven by pump beam **78** exhibits gain for signal beam **90** and idler beam **92** at signal and idler frequencies ω_S, ω_I (or, equivalently, at signal and idler wavelengths λ_S, λ_I) within the gain spectra dictated by primary wavelength λ_{pr}. Narrowband tuner **94** sets a narrow passband, as explained above, within the gain spectrum for signal or idler beam **90**, **92**. This narrow passband defines resonant frequency $\omega_{res.}$ of resonant beam **80**, containing a narrowband portion of either signal beam **90** or idler beam **92** supported by cavity **96**. In other words, narrowband tuner **94** rejects one of beams **90**, **92** and passes a narrowband portion of the other in the form of resonant beam **80**. The choice of which beam to pass will be made based on whether idler beam **92** or signal beam **90** will be used as output of light source **50**.

Resonant beam **80** travels through cavity **96** and a small portion, preferably just a few tens of percent of total power in resonant beam **80**, is out-coupled through output coupler **100** for the desired application. Except for the out-coupled power, resonant beam **80** is recirculated in cavity **96** by fiber **98** back into nonlinear converter **60**. Specifically, resonant beam **80** in-couples via taper **77** into waveguide **76** and then couples across directional coupler **86** into waveguide **62**. Once back in OPA **68**, resonant beam **80** experiences gain and is thus amplified on each round-trip through cavity **96**.

The tuning of resonant beam **80** is also performed in accordance with the general principles explained above. Specifically,

adjustment mechanism **58** changes primary wavelength $\lambda_{pr.}$ of diode laser **53** to shift the gain spectrum of OPO. At the same time, narrowband tuner **94** adjusts the location of the passband. In this manner, the new desired resonant frequency $\omega_{res.}$ is selected for resonant beam **80**.

Conveniently, in this embodiment adjustment mechanism **58** and narrowband tuner **94** are in communication via a connection **104**. In this combination, mechanism **58** and narrowband tuner **94** form a wavelength sweep control **106** for coordinated adjustment of primary wavelength $\lambda_{pr.}$ and hence of pump frequency ω_p and of resonant frequency $\omega_{res.}$. Preferably, narrowband tuner **94** keeps its passband centered at the desired resonant frequency $\omega_{res.}$ and mechanism **58** tunes pump frequency ω_p (by tuning primary frequency $\omega_{pr.}$) such that the passband remains centered at a maximum of the gain for either signal beam **90** or idler beam **92**. By coordinating narrowband tuner **94** and mechanism **58** in this manner, wavelength sweep control **106** can be set to perform a continuous wavelength sweep across the wavelength window available to resonant beam **80**.

Graph **51** in Fig. 5 illustrates the tuning behavior of signal beam **90** and idler beam **92** during OPO expressed in wavelengths, rather than frequencies. The wavelengths and wavelength ranges indicated in the graph are provided for explanatory purposes and will differ for alternate nonlinear optical materials (this plot based on dispersion of $LiNbO_3$). The dashed lines around graph **51** delimit a region of 3 dB gain for

optical parametric amplification. A change of primary wavelength $\lambda_{pr.}$ by 2 nm corresponds to a change of 1 nm of pump wavelength λ_p of pump beam **78.** Line A indicates degeneracy at which signal wavelength λ_S and idler wavelength λ_I are equal to 1530 nm. At this point, primary wavelength $\lambda_{pr.}$ is also equal to 1530 nm and pump wavelength λ_p is equal to 765 nm. A primary wavelength change $\Delta\lambda_{pr.}$ of merely 1 nm from 1530 nm to 1529 nm produces a pump wavelength change $\Delta\lambda_p$ of 0.5 nm and a corresponding signal wavelength change $\Delta\lambda_S$ of about 80 nm and an idler wavelength change $\Delta\lambda_I$ of also about 80 nm (since OPO is symmetric near degeneracy with respect to signal and idler beams **90, 92**). In other words, 160 nm of tuning of signal and idler beams **90, 92** (in the form of resonant beam **80**) is obtained with only 1 nm tuning of primary beam **54.** Similarly, the 2.5 to 3.0 nm tuning range **108** of primary wavelength $\lambda_{pr.}$ provides light source **50** with wavelength window **110** of 260 to 300 nm of for resonant beam **80.** A person skilled in the art will also note that the value of λ_p has a wide range ($\approx$300 pm) of acceptable values when λ_S and λ_I are within 1500-1580 nm.

The near degenerate operation results in a wide OPO gain bandwidth, while providing similar amount of gain to that obtained away from degeneracy. Also, near degenerate operation offers wide phasematching bandwidths for any type of phasematching used. Therefore, in the present, QPM grating **72** can be made long to improve the gain of the optical parametric amplification without sacrificing too much gain bandwidth or

sacrificing any tuning bandwidth. Most importantly, however, since only a very small amount of tuning of pump wavelength λ_p (in this case by directly tuning primary wavelength $\lambda_{pr.}$) results in a very large tuning of gain for signal and idler wavelengths λ_S, λ_I, the tuning operation can be performed rapidly.

As explained above, OPA **68** is not operated at degeneracy. Rather, OPA **68** is only operated with λ_s and λ_i within about 100 pm of degeneracy. Thus, tuning range **108** does not include a narrow offset **112** of about 100 pm from degeneracy.

Since optical parametric amplification is typically a low gain process, confining interacting beams **90**, **92** and **78** to first waveguide **62** is important for achieving high conversion efficiency. It is also important to make the length of OPA **68** and in particular the length of QPM grating **62** be as long as possible to achieve threshold and increase efficiency of the OPO. In addition, the power of pump beam **78** should also be high for efficient OPO. For example, the power level of pump beam **78** should allow for operation at two times threshold or above. A person skilled in the art will recognize that other changes can be made to ensure high conversion efficiency of the OPO (such as optimum output coupling and low loss).

Tunable light source **50** can be operated in continuous wave mode or pulsed mode. When operating tunable light source **50** in pulsed mode primary beam **54** is modulated. In particular, adjustment mechanism **58** not only tunes primary frequency $\omega_{pr.}$

but also modulates primary beam **54** to produce pulses **56** of a certain format. It is preferred, for efficient operation of OPA **68**, that primary beam **54** have a duty cycle ranging from 1% to 50%. Of course, other duty cycle ranges can be utilized.

For efficient OPO, pump beam **54** is synchronized with a round-trip time of resonant cavity **96**. This is done such that pulses **56** of primary beam **54** are synchronized with pulses **82** of resonant beam **80**. In one embodiment pulses **56** can be emitted after each round trip of resonant pulse **82**. Alternatively, pulses **56** are emitted at an integral fraction of the round trip time or an integer multiple of the round trip time.

Figs. 6A-B illustrate two alternative versions of arranging SHG **66** and OPA **68** in nonlinear converter **60**. The same reference numerals are used to designate corresponding parts. In the embodiment of Fig. 6A second waveguide **76** terminates in section **84** at directional coupler **86** which couples resonant beam **80** into first waveguide **62**. In contrast to the previous embodiment, SHG **66** has an aperiodic QPM grating **70A** of length L_1 for converting primary beam **54** to pump beam **78**. Aperiodic grating **70A** is designed to convert primary beam **54** to pump beam **78** over the entire ≈3 nm tuning range of primary beam **54**. Furthermore, length L_1 of QPM grating **70A** can be kept short (on the order of 1 cm) in this embodiment. Short length L_1 preserves space in nonlinear converter **60** and makes available a longer length L_2 for QPM grating **72** in OPA **68**.

In Fig. 6B directional coupler **86** is replaced by a directional coupler **87** serving a dual function. First, directional coupler **87** couples resonant beam **80** from waveguide **76** into waveguide **62**. Second, directional coupler **87** couples residual primary beam **54** remaining in waveguide **62** after SHG **66** into waveguide **76**. Residual primary beam **54** is guided away and damped in waveguide **76**.

Fig. 7 illustrates another tunable light source **120** for near degenerate OPO. Light source **120** has a pump laser **122** delivering a primary beam **124** at primary frequency $\omega_{pr.}$. An adjustment mechanism or pump tuner **126** is provided to tune primary frequency $\omega_{pr.}$. A synchronization unit **128** is provided to synchronize the timing of pulses in pump beam **124** with a round trip time of a cavity **130**.

Primary beam **124** is first in-coupled into a fiber amplifier **132** with the aid of a suitable optic **134**, e.g., a lens. Amplifier **132** can be an Er-doped fiber amplifier (EDFA) or another suitable amplifier. Amplifier **132** delivers amplified primary beam **124** to a nonlinear converter **136**, which performs second harmonic generation of primary beam **124** to derive a pump beam for driving optical parametric amplification. The details of nonlinear converter **136** are not specifically shown, as they are analogous to those of converter **60** of light source **50**.

Cavity **130** has a fiber **138** which is coupled to nonlinear converter **136** and coupled with the aid of lenses **140A, 140B** to

a narrowband filter **142.** A passband control **144** tunes the passband of filter **142** to select the desired resonant frequency $\omega_{res.}$ and pump tuner **126** adjusts pump frequency ω_p accordingly to adjust the gain spectrum. Pump tuner **126** and passband control **144** are connected such that their operation, i.e., the setting of the passband and adjustement of pump frequency ω_p, are coordinated.

A resonant beam **146** established at resonant frequency $\omega_{res.}$ is out-coupled from cavity **130** with the aid of a directional coupler **148.** Directional coupler **148** sends a portion of resonant beam **146** into a fiber **150,** from which an out-coupled beam **147** at resonant frequency $\omega_{res.}$ is obtained. Out-coupled beam **147** can be collimated or focused, as required, with the aid of a lens **152.**

Fig. 8 illustrates a swept wavelength system **160** employing a tunable light source **162.** Tunable light source **162** has a pump laser **164** whose pump wavelength ω_p is tuned by a pump tuning unit **166.** Light source **162** further includes a cavity **168** containing a nonlinear converter **170** and a spectral control unit **172.** Cavity **168** has an input coupler **174** for in-coupling a pump beam **176** from laser **164** and an output coupler **178** for out-coupling a resonant beam **180** at resonant frequency $\omega_{res.}$. Nonlinear converter **170** has a QPM grating **200** for phasematching optical parametric amplification of pump beam **176** near degeneracy.

In this embodiment, light source **162** is equipped with a wavelength sweep control **182**. Sweep control **182** is connected to pump tuning unit **166** and to spectral control unit **172**. Sweep control **182** is designed to sweep resonant frequency $\omega_{res.}$ across a portion of or the entire wavelength window available to light source **162**.

Resonant beam **180** obtained from light source **162** is used for performing a swept wavelength test of a device under test (DUT) **184** positioned on a test stage **186**. Resonant beam **180** is directed to DUT **184** by a mirror **188**, conveniently a movable or scanning mirror, and is focused on DUT **184** by lens **190**. A reflected beam **192** from DUT **184** is focused by a lens **194** on a photodetector **196**. A reflectance spectrum analyzer **198** is connected to photodetector **196** for analyzing the test results. The principles of swept wavelength testing in reflectance as well as transmittance modes are well-know to a person skilled in the art and will not be discussed here. Shown in Fig. 8 is a free-space (bulk optics) implementation of a swept wavelength test system. It is obvious to one skilled in the art that a fiber-based implementation can be constructed using, for example, a fused fiber coupler as the output coupler and where the devices under test (DUTs) are fiber-pigtailed.

In this embodiment the parameters of light source **162** are in accordance with test requirements. For example, when DUT **184** is a passive or active telcom component and the measurement has to be performed in a manufacturing environment, sweep

control **182** is optimized for speed. For example, sweep control **182** is adjusted to perform a sweep of the entire wavelength window within about 1 minute. In addition, the power level in resonant beam **180** is adjusted to be suitably high and the passband of spectral control unit **172** is set as narrow as required by the test. For example, in case DUT **184** contains small features, the passband of spectral control **172** is set to 0.1 to 10 pm or even less. The power level is set for 1 to 10 mW by adjusting power level of laser **164** and pulse synchronization, as discussed above. With these settings light source **162** will be able to support tuning rates of about 10-50 nm/sec or more and exhibits low noise, low amplified spontaneous emission (ASE) and polarized resonant beam **180**.

In the specific case of swept wavelength testing, light source **162** does not need to be limited to performing optical parametric amplification in nonlinear converter **170**. In fact, QPM grating **200** can be adjusted to the phase matching condition of other nonlinear frequency conversion processes driven by pump beam **176**. Appropriate nonlinear conversion processes are known in the art and can include second harmonic generation, difference frequency generation or sum frequency generation. All of these processes can be operated in the near degenerate range, as required to obtain a suitable resonant beam for swept wavelength testing from light source **162**.

In other variants of the invention it is possible, for example, to cascade several nonlinear steps to further broaden or shift the useful tuning range of the light source of the

invention, without departing from the principles of near-degenerate operation and pump-wavelength and/or primary wavelength tuning. The preferred embodiment described above makes use of SHG followed by an OPO step, resulting in wide tuning around the primary wavelength. It is also possible to cascade SHG, followed by OPO, followed by SHG. This embodiment results in tuning the ≈700 nm to ≈850 nm range when starting with a primary wavelength near 1550 nm. In another embodiment one can cascade SHG, followed by OPO, followed by DFG (difference frequency generation) with a fixed (or tunable) source at a secondary wavelength. This embodiment would result in tuning in the ≈2800 nm to ≈4500 nm range when starting with a primary wavelength near 1550 nm and a fixed 1064 nm source serving as the secondary wavelength. Yet another embodiment would make use of an OPO followed by 2 stages of SHG, resulting in a tunable source in the range of about 350 nm to 450 nm. Thus, although the present invention and its advantages have been described in detail, it should be understood that various changes, substitutions, and alterations can be made herein without departing from the principle and the scope of the invention. Accordingly, the scope of the present invention should be determined by the following claims and their legal equivalents.